

THE LARGE HADRON COLLIDER (LHC) IN THE LEP TUNNEL

by the LHC Working Group, reported by G.Brianti
CERN, CH-1211 Geneva, 23, Switzerland

Abstract While the LEP accelerator is being commissioned, the future of CERN is progressively focussed on a second collider for high energy proton-proton and proton-electron collisions to be installed in the LEP tunnel.

This report summarizes the main features of the collider and describes the more recent studies and developments :

- a trend towards higher luminosities up to a few $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ for pp collisions,
 - the R&D programme of superconducting magnets which has given promising results during the last 12 months,
 - the compatibility between a normal operation of LEP and the installation of LHC.
- The existence of the LEP tunnel, of the CERN infrastructure and of the existing machines as injectors makes the project particularly attractive from the economic point of view and for its achievement in a relatively short time scale.

INTRODUCTION

The first electron and positron beams are now injected and accelerated with success in the LEP collider¹, and the physics with high energy leptons will hopefully start in the near future. The long-term high energy physics research at CERN could then rely on proton-proton, proton-electron and heavy ion collisions which are all possible, providing a hadron collider is installed in the LEP tunnel.

A version of this Large Hadron Collider, LHC, has already been described² with a luminosity of $1.4 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$. Recent studies have shown that the discovery of a massive Higgs particle ($m_H < 0.8 \text{ TeV}/c^2$) seems possible at the LHC, provided a luminosity $L = 1$ to $5 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ could be reached³. This could be obtained through the process ($H \rightarrow ZZ \rightarrow 4 \mu$) using a multi-muon "beam-dump" detector. This paper summarizes the new LHC parameters, the recent results and trends of superconducting magnets, the new options in cryogenics, radiofrequency, injection and experimental areas.

HIGH LUMINOSITY PROTON-PROTON COLLISIONS

Recent experimental results with dipole models have shown that a magnetic field between 9 to 10 T can be reached. Since the circumference of the LHC orbit is determined by that of the LEP tunnel, it corresponds to a top energy of 8 TeV per beam.

A luminosity much higher ($3.8 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$) than the one of the initial design appears possible⁴:

- by reducing the β^* in the interaction region (I.R) from 1.0 m down to 0.25 m.
- by increasing the number of bunches, the interbunch spacing being 15 ns instead of 25 ns.
- by increasing the number of protons / bunch from 0.29 to $1 \cdot 10^{11}$ p, which is still compatible with the tolerable beam-beam tune shift ($\Delta Q < 0.01$ for the sum of the three insertions).

Two different insertions are now proposed :

- the high luminosity with $\beta^* = 0.25 \text{ m}$ and a free space of 6 m on either side of the interaction point.
- the medium luminosity with β^* which can be tuned from 5 m down to 0.5 m and a free space of 20 m on either side of the interaction point.

The general parameters of the machine⁵ are given in Table I.

The proton accelerators which are available on the CERN site provide adequate injectors even for this high intensity. In the LHC itself, careful compensation of the spurious multipolar components in the magnetic field, a smooth design of the beam vacuum chamber and sophisticated feedback systems will ensure a sufficient stability of the beams.

However the energy stored in the beam approaches 600 MJ, a considerable amount to be piped into superconducting magnets. The loss of even a tiny fraction of the beam could induce a quench of the magnets. In the high luminosity interaction region the power of the inelastic events is greater than 10 kW which have to be absorbed by the detector while a few kW of elastic events contributes to a blow up of the beam emittances⁶. Studies are going on to design effective protection for the magnets and adequate operational procedures.

LATTICE

Due to the size of the LEP tunnel cross section, installing two separate cryostats, one for each p beam, is not possible. The only way is to combine the two beams into the same magnet and the same cryostat. The superconducting coils providing equal but opposite magnetic fields have a common iron yoke and force-retaining structure (Fig 1), the whole being housed in one cryostat. This "two-in-one" solution allows the highest possible field in the restricted space

above LEP, and has not only the advantage of compactness but also of lower cost, compared with that of two independent rings with separate cryostats.

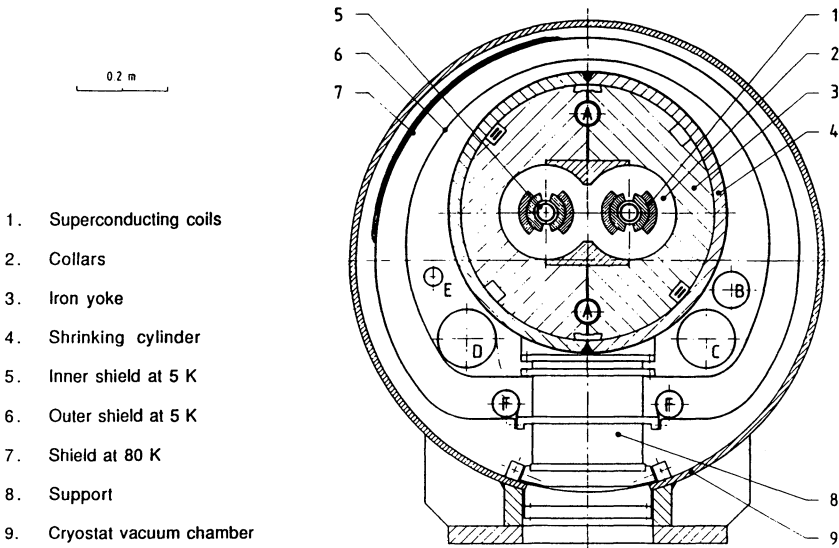


FIGURE 1 Cross-section of a LHC standard two-in-one dipole in its cryostat

LHC being in the same tunnel as LEP will also have 8 arcs and 8 long straight sections. The two proton beams, horizontally separated by 180 mm in the arcs, alternate from the outside to the inside in the middle of each of the 8 long straight sections, where in principle they could interact.

The LHC lattice of FODO type is constituted by :

- 8 arcs, each of them containing 49 half cells.
- 8 insertions, each of them containing one long straight section and two dispersion suppressors of a type that allows trajectories of identical length for the hadrons in LHC and for the leptons in LEP.

For each ring an antisymmetric design is adopted, in which corresponding quadrupoles have equal and opposite strength on either side of an interaction point .

One half of a regular cell (Fig 2) consists of four , ~ 10 m long, dipoles (D), a focusing (or defocusing) main quadrupole (Q). Near each main quadrupole and for each ring stand a tuning quadrupole (TQ), a vertical or horizontal dipole to correct the closed orbit (COD), a set of multipolar correctors sextupole (S6), octupole (O8), decapole (D10) and a beam observation station (BOM). Lumped correctors (S6+O8+D10) are also foreseen in the middle of the half-cell. All these magnets are superconducting.

TABLE I LHC parameters

| | | |
|---|-----------|------------------------------|
| Circumference (m) | 26658.833 | |
| Revolution time (μ s) | 88.924 | |
| Revolution frequency (kHz) | 11.246 | |
| Maximum beam energy for B = 10 T (TeV) | 8 | |
| Injection energy (TeV) | 0.45 | |
| No. of interaction regions (I.R.) | 3 | 1 High Lum. 2 Medium Lum. |
| Free space at I.R. | 12 | High Lum. |
| | 40 | Medium Lum. |
| Full bunch length (4s, m) | 0.31 | |
| RF frequency (MHz) | 400.8 | |
| Acceleration time (s) | 1200 | |
| Interbunch spacing (ns) | 15 | |
| No. of p bunches/beam | 4810 | |
| No. of p / bunch (10^{11}) | 1.0 | |
| No. of p / beam (10^{14}) | 4.81 | |
| Intensity / beam (mA) | 865 | |
| Energy / beam (MJ) | 597 | |
| Total synch. rad. (kW) | 18.3 | |
| Transverse emittance $4\pi \gamma \sigma^2/\beta$ ($\pi\mu$ m) | 15 | |
| Beam radius (2s) at $\beta^* = 0.25$ m (mm) | 21.3 | |
| Luminosity at $\beta^* = 0.25$ m (10^{34} cm ⁻² s ⁻¹) | 3.8 | |

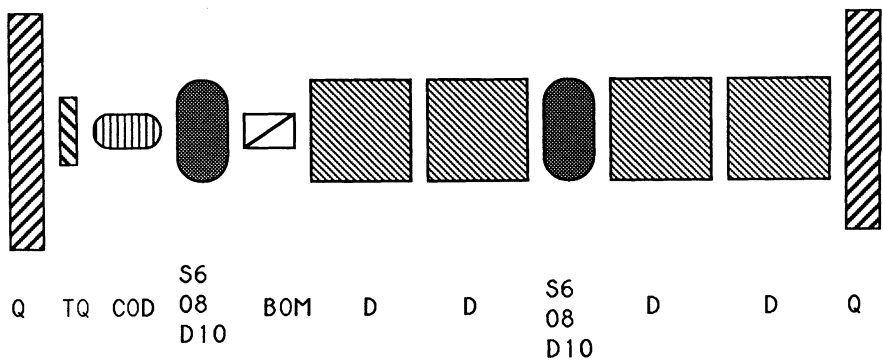


FIGURE 2 One half of a regular cell (schematic view)

MAGNET SYSTEM

As already reported ², a dipole field as high as 10 T can be obtained either with classical NbTi coils but cooled by He II at ~ 2 K or with Nb₃Sn coils, made with the "wind-and-react" technique and cooled by normal He at about 4.4 K.

The first method presents the advantage of a well understood magnet fabrication, but of a less conventional cooling with superfluid He, which has the very interesting features of great heat conductivity and low viscosity (coil "impregnation") but the drawback of a small

operational temperature margin over one LHC octant (~ 0.15 K). On the basis of current prices it should also lead to the lowest cost.

The advantage of the second method is a classical liquid He cooling with a relatively large operational temperature margin, but the serious disadvantage of a complicated method of coil fabrication, involving a heat treatment at ~ 700 C of the wound coils. If this method could be successfully developed, Nb₃Sn magnets could represent a serious alternative to NbTi magnets, either for the entire machine (in case of favourable economic conditions) or at least for the parts most exposed to the heat deposit by the beam tails.

Both technologies are being developed simultaneously at CERN in collaboration with European industries ⁷. Promising results were obtained with 1 m long, single aperture (50 mm) dipole models.

The NbTi models were designed and built as a joint project between CERN and the Italian firm ANSALDO. In April 1988 the first model passed its 8 T nominal induction without quench to finally reach 9.3 T (= 10400 A) at 2.0 K ⁸. Field rise time and intensity discharge time corresponding to LHC nominal values have also been achieved without quench. A second model of the same design, tested in July 1989 has shown a perfect reproducibility in the results and reached 9.45 T central field at 1.8 K.

The Nb₃Sn models were designed and built as a joint project between CERN and the Austrian firm ELIN. Each coil layer is wound with non-reacted and insulated Nb₃Sn cable. The finished coil layer is then placed, together with its mandrel and clamping system, into the reaction oven to be "reacted in situ". Only glass and mica tapes are used as interturn insulation which must withstand a reaction temperature of 700 C. The first half bore mirror magnet, tested at CERN in February 1989 reached 10 T at 4.3 K after 6 quenches. The main dipole magnet was tested in June 1989 and reached a central field of 9.4 T (=15040 A) at 4.3 K after 4 quenches. The corresponding maximum field on the innermost turn of the first layer was 10.05 T ⁹

To reach an operational field of 10 T in 10 m long "Two in One" dipoles, several other steps are being implemented. An extensive collaboration with National Institutes and European industries is under way. It concerns :

- the conductor and cable activity, both in NbTi and in Nb₃Sn technologies.
- the construction of four 10 T, 1 m long, NbTi twin aperture dipole models as a joint development between CERN and four European companies. Deliveries at CERN for test purposes are expected by Spring 1990. An agreement with FOM, UT and NIKHEF (NL) has been signed to develop a 10 T, 1 m long, Nb₃Sn dipole magnet using the "powder route".
- the construction of full length prototypes. A 7.5 T, 9 m long, twin aperture dipole, using the HERA-type windings (internal diameter = 75 mm) has been designed at CERN and

ordered to industry (ABB,Germany). It will allow to test the "two in one " concept with superfluid helium cooling. The full-size 10 m long cryostat has also been ordered (FBM,Italy). Cryogenic and magnetic tests are foreseen in early 1990. After the tests of the 1 m models, prototypes of 10 T, 10 m long, dipoles will be ordered.

- the design of the regular lattice quadrupole in collaboration with the French CEA, of the tuning quadrupole with a consortium of Spanish firms, and of the sextupole/dipole corrector with RAL (UK) and a British firm (Tesla).
- the design and tests of other important components such as current leads and high current diodes.

CRYOGENICS ¹⁰ (for NbTi)

The main task of the cryogenic system is to maintain all windings at a temperature below 2 K in steady operation, as well as to cope with slow and fast thermal transients such as cooldown, current ramping and discharge, and resistive transition of the magnets.

In steady operation, three heat sources are considered :

- the heat in-leak from the environment which essentially depends on the cryostat design. In the design of Fig. 1, the heat load at 2 K is estimated to be 0.15 W/ metre of dipole cryostat. The inner and outer radiation shields are maintained at 5 K, the second shield is maintained at 80 K..
- the ohmic heat load due to the resistive joints is also estimated to be 0.15 W/ metre of dipole cryostat .
- the beam-induced losses: (i) synchrotron radiation (critical energy < 63 eV) is fully absorbed by the inner radiation shield at 5 K inside the vacuum chamber; (ii) distributed beam losses due to beam-gas scattering are negligible, but an accidental scattered beam can produce a quench if the heat deposit in the dipole exceeds 25 W over 50 m. It is assumed that there is only one such high heat load per half octant.

Additional heat loads due to eddy currents are produced during ramping up and down of the magnet current. Those heat inputs can almost entirely absorbed by the heat capacity of the helium contained in the cryostat.

A cooling scheme based on forced circulation of superfluid helium is being considered (Fig. 3). It appears adequate to absorb transient and localized heat loads. A pump circulates a mass flow of superfluid helium in a closed loop extending over one half-octant, periodically recooled by heat exchange in distributed cooling stations located in the machine tunnel.

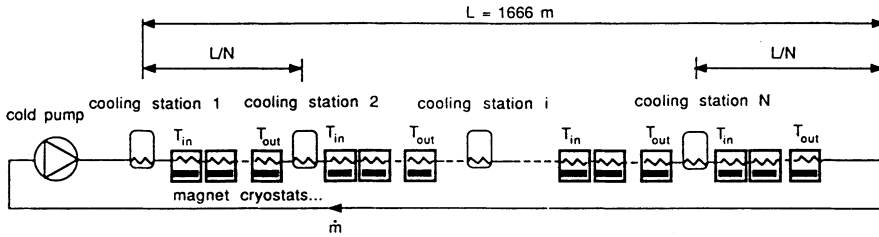


FIGURE 3 Basic forced-flow cooling loop

Some technical developments required by this scheme are being made in collaboration with the French CEA. Forced circulation of superfluid helium on a large setup is being experimentally tested at Grenoble. The thermal behaviour of an insulated coil cooled by superfluid helium is being studied at Saclay. Extensive cryogenic tests will be performed on the 10 m-long prototype cryomagnet. Magnetic refrigeration is also being investigated for the distributed cooling stations.

RADIO-FREQUENCY

The very high beam loading conditions which prevail for the high luminosity determine the design of the RF system. During storage, a large bucket (9.25 eV.s) accommodates high intensity bunches with their inflated longitudinal emittance. At the chosen RF frequency of 400.8 MHz, this corresponds to $V = 18 \text{ MV}$. The total RF power per beam that the generators must be able to provide ($P \approx VI_b/2$), in order to handle beam loading in the cavities, amounts to 8 MW for the high average beam current ($I_b = 0.86 \text{ A}$) needed for the high luminosity. Only a small fraction (850 kW) of the total installed power is dissipated in the cavity walls, which gives little incentive for choosing superconducting cavities.

One of the lateral dimensions of the cavities ($\pm 15 \text{ cm}$) is constrained by the distance between beams (18 cm). Compared to the original cylindrical cavity², a better shunt impedance ($4\text{M}\Omega/\text{cell}$) and an easier cooling can be obtained with a rectangular geometry. Each 1 MW power generator (8 per beam) drives a 6 cell π mode coupled cavity (2.25 MV at 1 MV/m); this is a favourable arrangement to implement RF feedback needed to handle beam loading. Although klystrons offer a relatively straightforward solution for the 1 MW power sources, their efficiency is not very high for this particular mode of operation, where average power is much smaller than peak power. High power gridded klystrons, working in

class B, recently appear on the market, and associated with circulators seem an interesting solution for the LHC.

INJECTORS, BEAM TRANSFERS AND DUMPING

The injection into LHC uses the CERN complex of existing accelerators : Linacs, Booster, 26 GeV PS, 450 GeV SPS. In p-p mode the LHC bunch spacing is already formed at top energy in the PS by a dedicated RF system. The bunches are then compressed in the PS to fit into the 200 Mhz buckets of the SPS. After box-car stacking of PS pulses in the SPS, the beam is accelerated to 450 GeV and transferred to LHC. According to the beam intensity required, this is repeated 4 to 12 times for filling each LHC ring.

To reduce the injection time where persistent currents vary with time, a new transfer scheme has been adopted, which avoids the polarity reversal of the SPS. It consists in filling (Fig. 4) :

- clockwise one LHC ring via a transfer line starting in the SPS sextant 5 to inject into the LHC octant 1,
- anticlockwise the other LHC ring via a transfer line starting in the SPS sextant 4 to inject into the LHC octant 8.

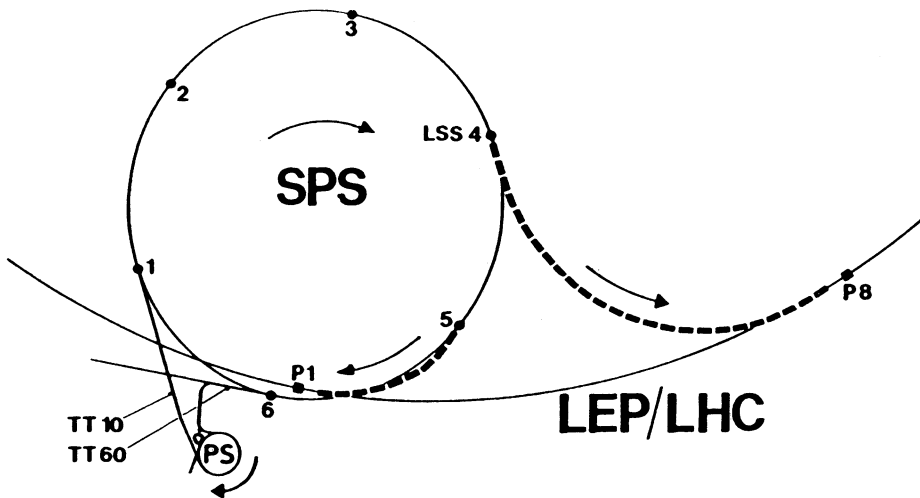


FIGURE 4 LHC injector chain

Dumping the high power LHC beams requires that the absorber blocks are located in caverns with enough shielding to protect the environment and to allow safe access to the LEP

tunnel during shut-downs. Both proton beams will be extracted at intersection 3 and transported to a cavern via a transfer line of small diameter.

EXPERIMENTAL AREAS

Two kinds of experimental areas have been studied so far.

One can house a large general purpose detector, in so far as its dimensions and structure can be deduced from the workshops dedicated to LHC physics^{11,12}. The conceptual design of the area consists in two identical cylindrical caverns. One is centred on the beam axis and the other one, parallel to it, is for the construction of the detector and also to serve as a garage for maintenance and to allow for further LEP operation. Civil engineering studies have shown that the useful diameter of the caverns could be as large as 24 metres, allowing for the installation of a detector of diameter of about 20 metres. The detector could weight up to 50000 tons. The magnetised iron of the muon filter and spectrometer would be the heavy part of the detector and should be built in the beam position. It would then serve as a support and a shell for the mobile inner components. A similar, but somewhat smaller area can satisfy the needs of an e-p detector.

The other type of experimental area is for the highest possible luminosities where the detector should be rather compact, due to the absence of a large central tracking device¹². Its overall size should be such that it could be installed in a slightly modified LEP-like area. The detector, weighting approximately 10000 tons could be moved in and out as one single piece without going beyond the possibilities of known technologies. The access to this detector would then be made very flexible.

CONCLUSIONS

Most of the civil engineering around the experimental areas, starting with the access pits and the garage, and also most of the detector construction could be done while LEP is operating. The magnet and cryogenics installation will require a shut-down of 14 to 18 months in total, which can be subdivided in two or three periods of 6 to 8 and 10 to 12 months. All the other machine systems can be installed during the same periods. Extended over three years, the LHC installation will then not compromise the LEP operation, which was originally foreseen to be 4000 hrs per year.

A workshop on radiation protection was held at CERN in May 1989 with the participation of experts from other laboratories. The conclusions were that for the beam

intensity and energy assumed in this paper the dose equivalent rates at the ground surface are negligible as well as the quantities of radionuclides reaching the environment¹³.

The exploitation of LEP and LHC in the same tunnel is not only compatible, but is of considerable interest for collisions between protons and electrons. Furthermore the current CERN experience in accelerating ions allows one to envisage collisions between ions in LHC.

In those conditions, with the availability of the LEP tunnel, of the existing injectors and of the general CERN facilities (infrastructure, offices, workshops, general services), considerable savings can be made in the cost of LHC. During the last years, CERN has devoted the major part of its manpower and budget to the LEP construction. This period is coming to an end with the recent encouraging beam performances of the LEP. CERN staff will soon become available to work on the LHC project.

The best time scale to start the commissioning of the LHC would be in 1996-97. It would allow its design to be finalized during the next 2 years, while the production of HERA magnets will be completed and the full ring commissioned; the know-how of the European industries and national institutes, acquired during the present active phase of building models and prototypes, could then be transferred to the production and test of the LHC magnets. The duration of this production (a maximum of 4 years) and the completion of all other systems (minor work with respect to the magnet system) would be fully compatible with the commissioning of the full LHC in 1996/1997.

REFERENCES

1. LEP preliminary beam tests. To be published.
2. G. Brianti and K. Hübner. CERN 87-05, Mai 1987.
3. The feasibility of experiments at high luminosity at the large hadron collider, Geneva, CERN 88-02, April 1988.
4. J. Gareyte. LHC Note 70, February 1988.
5. L. Burnod, J. Gareyte. LHC Note 92, May 1989.
6. L. Burnod, J.B. Jeanneret. LHC Note 91, April 1989.
7. R. Perin. IEEE on Magnetics, vol 24, March 1988
8. R. Perin et al. Proc. ASC, San Francisco, Aug 1988
9. A. Asner et al. To be published MT11 Conf. Sept 89.
10. G. Claudet et al. Proceedings of the 12th ICEC. Butterworth 1988. p 497.
11. Large Hadron Collider in the LEP tunnel, Lausanne 1984, ECFA 84/85, CERN 84-10, 2.09.1984.
12. Proceedings of the workshop on physics at future accelerators, La Thuile 1987, CERN 87-07, 4.06.1987
13. Minutes of a workshop on LHC environmental considerations. To be published.